8 DEVELOPING AN EMERGING TECHNOLOGY ROAD MAP FOR CARBON CAPTURE AND SEQUESTRATION

Vision

Emerging technology road maps furnish a framework for managing and reviewing the complex, dynamic R&D process needed to achieve important strategic goals.

8.1 INTRODUCTION

Road-mapping techniques are being used by numerous industrial firms, industry collaborative groups, and government agencies in their planning processes. The term “road mapping” has been broadly applied to many kinds of activities, and there are many types of road maps.

The purpose of an emerging technology road map is to provide—and encourage the use of—a structured scientific R&D planning process. Emerging technology road maps furnish a framework for managing and reviewing the complex, dynamic R&D process needed to achieve important strategic goals. These road maps show graphically how specific R&D activities can create the integrated technical capabilities needed to achieve strategic objectives. This chapter describes the creation of an emerging technology road map for the capture and sequestration of CO_2.

8.2 A CARBON CAPTURE AND SEQUESTRATION SYSTEM

An emerging technology road map seeks to identify the scientific and technological developments needed to achieve a specific technology goal. The process of identifying the needed science and technology must be focused by developing a concept of the technological system that would enable achievement of that goal. This task is particularly difficult in the case of carbon capture and sequestration because there is no paradigm for such a system.

Today, carbon is emitted to the atmosphere from energy technologies that were not designed to capture, let alone sequester, these emissions. There are many ideas for, and even demonstrations of, technology to capture and sequester carbon from fossil fuel combustion. However, we must consider that the current energy system could be modified significantly to make an economical capture and sequestration system possible. Thus the emerging technology road map for carbon capture and sequestration cannot be constructed apart from consideration of current and emerging energy technologies. It will involve an iterative process to connect this road map with others being developed by DOE for various parts of the energy technology system.

Figure 8.1 gives a top-level picture of a carbon capture and sequestration system and its linkages to the energy system. Within the current fossil energy system, carbon is processed in several forms by different fossil fuel technologies in many different parts of the energy system. To keep it from being emitted to the atmosphere, this carbon must be captured, processed in some way to separate or purify it, and changed to a solid, liquid, or gaseous form that is convenient for transport. It can then be transported in an engineered system to a site for sequestration or for transformation into a long-lived end product. Alternatively, the carbon could be emitted as CO_2 and transmitted through the atmosphere if sequestration by bio-absorption can be assured in some part of the natural carbon cycle.

This report has concentrated principally on the new scientific understanding and technology (shown in white in Fig. 8.1) that are needed for specific capture and sequestration functions. Transportation technologies (shown in gray) have not been addressed. However, particularly in Chaps. 2 and 7, reference is also made to specific changes in components of the existing energy system (shown in black) that would simplify and/or lower the cost of capture and sequestration.

The close relationship between fuel transformation—from natural hydrocarbons to refined fuels for transportation and/or dispersed energy technology—is of particular importance in this regard. Changes in the carbon content of refined fuels can alter the flow of carbon through the capture and sequestration system. Lowering the carbon contents of transportation fuels can change the balance between carbon transported through the atmosphere and that which must be handled in potentially more expensive engineered systems. The form of fossil-fueled electricity-generating technology also plays an important role in determining the form and cost of capture and sequestration technology. The cost and applicability of the individual capture and sequestration technologies shown depends fundamentally on the particular fossil-fueled electricity-generation technology employed. These are two areas for particular emphasis in coordinating this road map with other DOE transportation and fossil energy technology road-mapping efforts.

The major capture and sequestration technologies are listed in Fig. 8.1 and are discussed in detail in Chaps. 2–7. Each can be developed and improved individually. However, the economic cost and effectiveness of the overall carbon capture and sequestration system depend on the effective combination of many technologies.

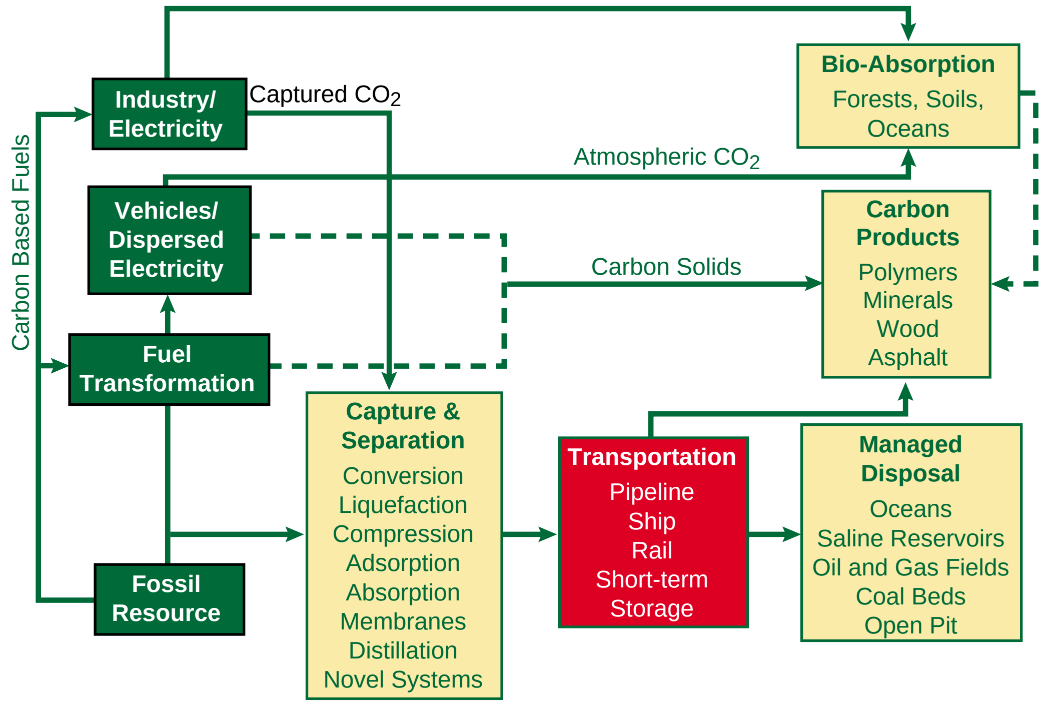

Fig. 8.1. The top-level diagram of a carbon capture and sequestration technology system showing the relationship to the fossil energy system.

Their relative importance must finally be judged in the context of the integrated technology system. The system shown in Fig. 8.1 is adequate for taking the first steps in developing a carbon capture and sequestration emerging technology road map, but a more detailed system engineering effort will be required to add economic and engineering substance to this sketch before the requirements needed to plan an R&D program can be generated.

8.3 BUILDING AN EMERGING TECHNOLOGY ROAD MAP

After identifying the technology goals and the integrated technology system needed to satisfy those goals, the next step in developing an emerging technology road map is to assess the alternative technological pathways that might lead to achieving the integrated technology system. The approach is to construct these pathways within a technological hierarchy. The highest level of the hierarchy is the integrated technology system—in this case, the carbon capture and sequestration system. The hierarchy ends with the science and technology capabilities that are needed to develop the technologies that make the system economical and effective.

Analyzing the integrated technology system in terms of its component functions and the performance required to meet the strategic goal connects these extremes. First, we identify the critical technology platforms that might provide high value in the operation of the integrated technology system. The technological components that make up the technology platforms can also

Definitions of the Technology Hierarchy

Technology platform: A combination of components; intellectual property; and market, business, and technical know-how that can be applied to a family of process needs.

Component: A technology or specific knowledge that performs, or allows the performance of, a unit function supporting one or more technology platforms.

S&T Capability: General science, engineering, and management knowledge and skills that enable development of components and technology platforms.

frequently be identified within the integrated technology system. However, the performance or development requirements of these components must be determined from the needs of the technology platforms, which are aimed at increasing the economic performance of the whole system.

As applied to emerging technologies, the hierarchy includes technology in different stages of development. In fact, not all of the science or technology in an emerging technology road map is well defined. Some elements may well be represented by little more than functional requirements and a technical intelligence–gathering plan to identify scientific or technological approaches. Thus after assembling the framework of the road map by working downward through the hierarchy from policy goals to capabilities, one must also work upward from the capability level to identify possible pathways and to map a course of development.

8.4 BUILDING THE CARBON CAPTURE AND SEQUESTRATION ROAD MAP

Chapters 2–7 are organized by related areas of scientific expertise. These chapters were prepared by experts in each science and technology area that would be needed to develop a carbon capture and sequestration system such as that shown in Fig. 8.1. The material provided by these expert groups is the foundation for developing a carbon capture and sequestration road map.

To develop the outline of an emerging technology road map from this material, the carbon capture and sequestration system outlined in Fig. 8.1 was broken down into its functional components. The result is shown graphically as the capture and sequestration technology system in Fig. 8.2.

Then, using the Graphical Modeling System (GMS), an integration group asked each of the working groups to identify technology platforms that they believed would be critical for the efficient performance of these system functions and that were particularly dependent on the group’s science and technology. Within these technology platforms, the groups were asked to identify specific components, again within their science and technology areas, that they believed could be important to the development of these technology platforms. Finally, each group was asked to identify the science and technology capabilities that would be essential for the successful development of the technology that they had identified. They also specified the relationships between the science and technology at each level within this science and technology hierarchy. This exercise enabled each of the working groups to better perceive the

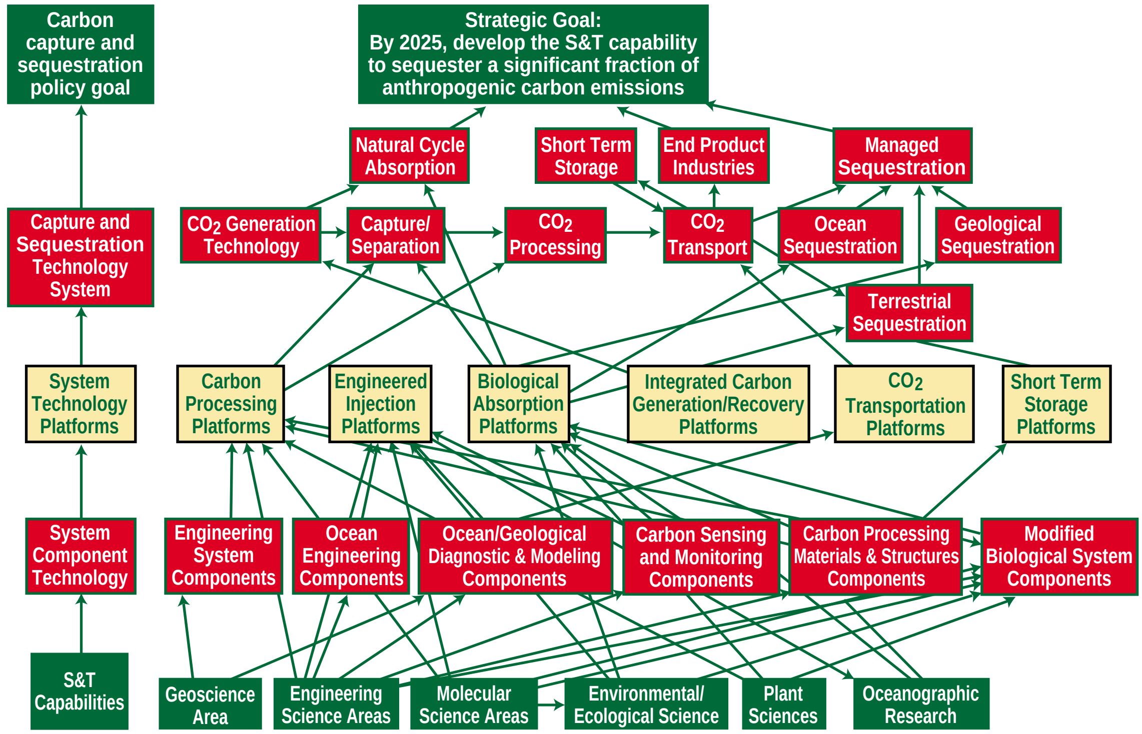

Fig. 8.2. The structure of an emerging technology road map for carbon capture and sequestration. The boxes (nodes) contain the science and technology needs developed by expert working groups in Chaps. 2–7. The lines represent the relationships and performance requirements among technologies.

relationship of its particular technical area to the overall carbon capture and sequestration system. Each of the working groups also adapted this general approach to better illuminate the technical discussion in its chapter.

The integration group assembled all of this expert input into a system-level outline of an emerging technology road map (Fig. 8.2). The outline illustrates the complex inter-dependence of the science and technology described in the preceding six chapters. To achieve the capability to capture and sequester a significant fraction of anthropogenic carbon by 2025, development is required at each level of this hierarchy supporting a fully functional carbon capture and sequestration system. Even at this stage in the development of a road map, the need for a coordinated science and technology development program is evident from the many science and technology relationships shown in Fig. 8.2.

The science and technology underlying the nodes at each level of the hierarchy in Fig. 8.2 is discussed in more depth in Chaps. 2–7. Each of these items is also shown in summary fashion in Tables 8.1–8.3. Working from the bottom to the top of Fig. 8.2, to support the carbon capture goal, the next step is to assemble the capabilities, develop critical components, create new technology platforms, and integrate them with old technology to form a new carbon capture and sequestration system. From the capability to the systems level, technology becomes increasingly

Table 8.1. System technology platforms

Carbon processing technology platforms	Engineered injection platforms	Biological absorption platforms	Integrated carbon generation and recovery platforms	CO_2 distribution and storage platforms
Durable material processing	Geologic injection	Soils	CO_2 recycle combustion	CO_2 hydrates and transportation
Low-temperature distillation	Ocean injection - Tankers - Pipelines	Ocean fertilization	Chemical looping combustion	
Adsorption technology		Algal absorption systems	Biomass fuel production	
Membrane separations		High-productivity plants		
Absorption technology		Microbial CO_2 absorption		
CO_2 to fuels processing		Agricultural systems		
Bio-mimetic processing		Forests		
Clathrate processing				
Microbial biochemical reactors				
Carbonate processing				

integrated as it moves from the research laboratory to commercial application. In the past, these stages of development were often sequential. Today, they are more often overlapping in time and involve extensive interaction through the development and commercialization process. Exploring the path from science to system application consists of identifying the expected technology needs and performance requirements at each level of integration and mapping the relationships between them.

8.5 BUILDING THE R&D CAPACITY

The road mapping presented in this chapter leads to a three-pronged approach to R&D:

- Specific fundamental scientific breakthroughs in chemistry, geology, and biology that are necessary to achieve the vision presented in Chap. 1 are described below and in Chaps. 2–7.
- Large-scale field experiments would help scientists understand the efficacy, stability, and impact of stored carbon, as well as its consequences on humans and the

Table 8.2. System component technologies

Engineering system components	Ocean engineering components	Geological diognostic and modeling components	Carbon processing materials and structure components	Modified biological system components
Solids handling	Deep sea structural engineering	Reservoir characterization	Catalysis components	Species selection and genetics
Process CO_2 reduction	Hydrate formation technology	Reservoir distribution identification	Gas-liquid contactors	Crop and land management
Corrosion control	Drilling and injection	Geo-monitoring technology	Gas-solid contactors	Photosynthetic system enhancement
Byproduct extraction	Injection mixing and stability		Molecular sieves	Microbial rhizosphere enhancement
Carbon sensor technology	Plume modeling		Enhanced heat and mass transport technology	Soil improvement
In situ ocean carbon monitors			Solvents	Controlled eco-physiology
Tracer technology			Assembling macro-carbon structures	Ecosystem management
			Adsorbents	Fertilizer design and delivery
			Electro-swing adsorption materials	Microbial CO_2 transformation
				Environmental technology
				CO_2 fixation optimization

environment. These might be accomplished by piggy-backing on projects being conducted for other purposes in collaboration with industry, other federal agencies, and/or international programs.

- A coordinated program would take advantage of advances in basic research and findings from field studies. These data and conclusions should be coordinated, communicated, and integrated to better target additional scientific research and the design of future field experiments.

8.5.1 Advanced Sensors and Monitoring Systems

This three-pronged approach is supported by three system technology

Table 8.3. Science and technology capabilities

Engineering science areas	Geoscience areas	Chemical and molecular science areas	Environmental/ ecological science areas	Plant science areas	Oceanographic research areas
Reactor design	Multiphase flow	Surface modeling	Ecosystem modeling	Plant physiology	Ocean general circulation modeling
Large system engineering	Fluid dynamics	Kinetic modeling	Ecological monitoring - Field testing - Long-term stability	Plant pathology	Ocean chemistry
Environmental design	Geochemical reactions and kinetics	Molecular modeling	Ecological inventories	Metabolic engineering	Oceanic biosphere
Process design	Reservoir modeling	CO_2 hydrate chemistry	Environmental impact assessment	Genetic engineering	
Multiphase flow	Geophysical detail resolution	Heterogeneous chemistry	Ecosystem dynamics	Molecular biology	
Fluid dynamics	Geomechanics - In situ stress - Reservoir leakage and integrity	Chlorine chemistry	Microbial ecology (genomics)		
Environmental design		Physical chemistry			
Process design		Molten salt chemistry			
Reservoir modeling		Soil bio-chemistry			
Geophysical detail resolution		Material synthesis			
Geo-mechanics - In situ stress - Leakage/ integrity					

platforms and one system component technology that cuts across all focus areas.

The cross-cutting systems component technology is advanced sensors and monitoring systems. There is a continuing need to build more robust and sensitive sensors for measuring various biological and chemical species. These sensors need to be developed for making precise and accurate measurements in remote and/or hostile environments. Continuous improvements must also be made in monitoring systems to ensure that data are available in real time and the overall measurement systems will operate under a variety of conditions. The need for advanced sensors and monitoring systems is important for four reasons: (1) The nature of separation, capture, storage, and removal of CO_2 from the atmosphere needs to be quantified in order to measure the efficacy of the technology. Without such characterization, it will be difficult to understand the underlying processes. (2) The stability of the sequestration methods must be validated. We need to know how long the carbon will stay. This will be particularly necessary for oceanic, terrestrial, and geological sequestration. New sensors will need to be developed to measure carbon speciation in soils and CO_2 chemical and physical behavior in geological formations. (3) We must have measurement systems to evaluate impacts due to carbon sequestration. These impacts will need to be shared with the public. This will require development of sensors and monitoring systems for measurement of possible impacts in ocean, geologic, and terrestrial reservoirs. (4) Carbon sequestration will need to be monitored and verifiable if it is to play a role in international agreements.

8.5.2 Carbon Processing Platforms

The first technology platform is carbon processing. The focus of this platform is the development of advanced chemical technologies, which are in turn platforms for capture and separation and the development of technologies with collateral benefits. The effectiveness of capture and separation technologies in isolating relatively pure CO_2 for transport and sequestration will also determine the potential efficacy of geological and ocean sequestration options. The technology platforms that will be required include:

- Chemical/physical absorption, such as the synthesis of novel absorbents
- Chemical/physical adsorption
- Advances in membrane technologies, such as the development of polymeric membranes for increasing dissolution/diffusion rates
- Mineralization/biomineralization, such as developing better reaction paths for formation of carbonates and bicarbonates for geologic and ocean dissolution and sequestration
- Low-temperature distillation systems
- Novel concepts, such as better methods for producing CO_2 clathrates and use of algal bioscrubbers on emissions streams

Capture and separation technologies can also be developed based on engineering and/or chemistry advances of existing technologies already being used in industries such as oil and gas refineries. An important side benefit can be the capture and separation of hydrogen to be used as a clean fuel.

Advances in chemistry research can specifically support oceans and geological sequestration. Geological sequestration will require a better understanding of corrosion, as well as of silicate/carbonate complex interactions. Research will be needed in chemistry and materials sciences to support these geological options. Chemical research in biomimetic processing and the production of clathrates can enhance the effectiveness of engineered solutions for the sequestration of CO_2 in the oceans. In particular, the ability to sequester carbon as bicarbonates or carbonates cost-, resource-, and energy-efficiently will markedly increase the time for which carbon is effectively sequestered.

Chemistry research also has the best potential for developing collateral benefits. Carbon species can be manufactured into commercial commodities, thus giving sequestration an additional economic driver for commercialization. Two problems exist with this approach. First, removing carbon prior to combustion may increase its economic potential but will reduce its energy content. Second, the current market cannot properly use the potentially large amounts of carbon-containing materials produced as part of these processes. New markets and uses will need to be created. Some of these may be in the development of durable materials that could be used for construction materials or soil amendments. Other enabling technologies that would be developed as part of this research would include new catalysts, chemical sensors, and manufacturing process chemicals.

It is important to note that, while there is a huge amount of information on the inorganic and organic chemistry of carbon dioxide, sequestration needs will require new breakthroughs.

8.5.3 Biological Absorption Platforms

Biological absorption is the second system technology platform. Scientific research in this area will be necessary to enhance the ability of terrestrial and soil sinks to sequester CO_2, which will be based on advanced biological research. Plant sciences must develop new rapid-growing species and new, commercially viable woody species. Genetic engineering and molecular biology advances must be used to create new plant species and enhance microbial rhizospheres to increase plant productivity. Research must be done to increase understanding of soil biogeochemistry to enhance carbon uptake and sequestration in soils. As is the case with ocean sequestration, ecosystem dynamics must be better understood to evaluate potential impacts of new farming methods, introduction of new species, control of pests, and increased carbon content in soils. Finally, a potential way of enhancing ocean sequestration may be coupled with advanced biological research. Bioengineered solutions for increasing the primary productivity of oceans will allow for improved biological mechanisms of increased CO_2 uptake. Additionally, the development of algal scrubbers for CO_2 separation and capture may enhance technologies in this area.

8.5.4 Engineered Injection Platforms

The third key system technology platform is engineered systems. The emphasis for sequestration in oceans and geological sinks is similar: although progress has been made in the geological arena, improved injection systems must be developed to enhance the delivery of CO_2 to these sinks. In addition, many research advances in chemistry will require innovative engineered systems to effectively implement new technologies.

All of these findings are interrelated. For example, ocean and geological sequestration will not be effective unless efficient capture, separation, storage, and transportation technologies are developed to deliver CO_2 to sink locations. Capture and separation technologies in turn must rely on advances in chemistry and concomitant engineered solutions to make these technologies efficient and cost-effective.

It is clear from Tables 8.1–8.3 that the technology platforms are not all equally developed. One of these platforms, short-term storage, has not been examined at all because the carbon capture and sequestration system has not yet been sufficiently specified. It is included simply because the current natural gas transmission system, although small by comparison to an eventual CO_2 transmission system in terms of gas volume, requires large short-term storage capacity to operate.

Other platforms, such as integrated carbon generation and recovery, are bridges to other road-mapping efforts. For instance, the road map supporting Vision 21 (a proposed description of the future evolution of fossil fuel technology) is considering modifications to fossil power systems that could significantly simplify the capture of CO_2. Some platforms, such as CO_2 transportation or engineered injection, are brief because of an assumption that a great deal of experience has already been accumulated in these areas. This assumption will require further examination after a more detailed system engineering picture of a carbon capture and sequestration system is developed.

The most elaborated platforms are carbon processing and biological absorption. This is natural for the carbon processing platform because of the wealth of known chemical engineering techniques that might be adapted to this problem. This platform will become more focused as the conditions under which carbon must be captured and processed become more clear from system analysis and other energy and fossil fuel transformation road maps.

On the other hand, one might expect the elements within the biological absorption platform to expand even further as the wealth of possibilities presented by progress in the biological sciences is further explored. This richness is also reflected in the technology components supporting this platform.

The inclusion of the biological absorption platform is a genuine departure from traditional lines of energy technology development. It brings with it ties to agricultural and ecological research that have been tenuous at best in the history of energy development. Once carbon capture and sequestration become a feature of energy planning, scientific and technological progress in these fields assumes a key role in future energy development.

Recognizing linkages between disparate fields of knowledge such as these is a key feature of the road-mapping process. Developing and exploiting these linkages requires further effort.

8.6 NEXT STEPS

This chapter has described the first stage in developing an emerging technology road map for carbon capture and sequestration. Starting from a potential DOE policy goal, the technology system to achieve that goal has been sketched out. The areas of scientific and technological development needed to support this general technology system have been identified, including new areas foreign to traditional energy technology development.

Although mutual relationships and dependencies of scientific and technological development in all of these fields have been identified and are indicated by the links in Fig. 8.2, the corresponding performance requirements have not yet been developed. Nor has the phasing of potential R&D schedules been considered. Overlaps have been eliminated to some extent, but priorities and gaps in the technology needs have not been examined. More work needs to be done on specifying the economic constraints and technology needs of the integrated carbon capture and sequestration system illustrated in Fig. 8.1. This work can be done in parallel with the steps outlined in the following paragraphs, but it must be done to provide substance to the final road map.

The road map outline described is a valuable product. It should be used as a framework for Phase II of the Carbon Sequestration Road Map in developing a quantitative evaluation of the science and technology requirements for a carbon sequestration system. This is an essential aspect of building a usable road map with all of the requisite characteristics.

Road maps should integrate planning and implementation. The road map should consider all the plans of the organization, such as mission and visioning, market analysis, and portfolio analysis. But it goes beyond mere vision to develop a general plan for developing capabilities. Actionable items should naturally flow from the road map. The primary purpose of the emerging technology road map is to influence future events, not to predict them. Program objectives set for the future should, of course, be based on realistic expectations about market, policy, and technical trends. However, no one can predict the future. The value of emerging technology road maps derives from the fact that the future can be shaped by new technological developments. Road maps are intended for revision. A road map is not a plan for the future that is unchangeable when it is completed. As events unfold and new research results emerge, the plan must be changed to address the most current state of knowledge—and to build beyond the new frontier. The road map should provide a mechanism for accommodating serendipity—external events and new research results that should be incorporated into the technology development plans. The process of reaching a consensus is as important as the product. To be truly effective, the road map should be a vision of the future reached by consensus among all parties who have responsibility for the R&D—the funders, developers/deliverers, and implementers/users of technology.

Thus, the process of road mapping is as important as the final product of the process—the road map itself. Frequent communication with upper management along the way, involvement of all layers and functions of the DOE organization, and stakeholder participation are keys to success. Based on the results obtained so far, the stakeholders include other government agencies and the agricultural industry in addition to the energy industry. Many different views and priorities must be considered and synthesized into a coherent plan to carry out R&D on carbon capture and sequestration. This will develop the support needed as DOE attempts to implement the emerging technology road map.